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PRECIPITATION OBSERVATIONS FROM SATELLITES[1,2]

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ABSTRACT

The suggestion that a weather radar or other precipitation-monitoring device be incorporated in future meteorological satellites is examined. Because of the variability of precipitation patterns, instantaneous observations of them cannot be used to locate fronts or low-pressure centers with any accuracy, or to identify fronts. Useful extrapolation of precipitation data is limited to 50-100 miles[3] in space and to about 1 hour in time. Consideration of this result, in the light of orbit mechanics, shows that a single satellite cannot serve as a satisfactory monitor of precipitation over the entire earth.

1. INTRODUCTION

The photographs of the earth's cloud cover obtained by TIROS I were remarkable for a number of reasons. For the first time, meteorologists were able to view the earth's cloud cover from above on a systematic basis. The instantaneous field of view, 800 miles across, exceeded that of a surface observer by a factor of several hundred. The photographs showed clearly the cloud systems associated with both synoptic-scale and mesoscale pressure disturbances. The former conformed quite closely to the models developed years earlier, notably by Bjerknes (1), by combining surface observations.

Several individuals had suggested even before TIROS I was launched that a weather radar might be carried on a satellite to provide precipitation measurements on a global, round-the-clock basis [Wexler (2), Widger and Touart (3), Mook and Johnson (4)]. Further consideration showed that difficulties in beam shaping and in discriminating between precipitation and surface clutter return would limit observations to points within 20 miles of the satellite subpoint [Anon. (5) and (6)].

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[1] Prepared for presentation at the 44th Annual Meeting of the Pacific Division, American Association for the Advancement of Science, Stanford, California, 19 June 1963.

[2] This paper is based upon work performe[redacted]nder Contract No. NASr-49(06) of the National Aeronautics and Space Administration.

[3] Nautical miles are used throughout this paper.

The use of Doppler techniques to overcome this limitation, suggested independently by a number of writers, has been examined in detail by Hilleary (7) and rejected as impractical.

Figure 1 shows the contrast between the visual and radar situations. While the use of ground-based radar effectively extends the observer's field of view, a radar mounted in a satellite has a field of view which is not only smaller than that of satellite cameras, but is only a small fraction of the coverage it could provide at the surface. It is conceivable that this limitation could be offset by the satellite's motion. A satellite in a polar orbit at an altitude of 600 miles would travel at 4 mi/sec and pass over every continent and ocean at least once every 12 hours, although successive equator crossings would be 1600 miles apart. The worth of precipitation observations from a satellite depends upon the statistical nature of precipitation, in particular, upon the spatial and temporal variations in precipitation intensity.

2. THE NATURE OF PRECIPITATION

A. Precipitation Patterns as a Function of Synoptic Situation

The correlation of precipitation forms and intensities with the features of synoptic weather charts is accepted by meteorologists as a matter of course. The spiral rain bands of tropical storms are well known, and some composite radar photographs of line storms show good agreement with surface frontal positions [e.g., Senn and Hiser (8), Smith and Ligda (9)]. However, attempts to fit instantaneous precipitation distributions to fronts and pressure patterns, taken as a whole, have not been notably successful [Austin and Blackmer (10)], and neither have attempts to relate them to specific features in TIROS photographs.

Radar has shown that precipitation tends to form in discrete cells, which are organized into systems covering a few hundred to several thousand square miles. These systems, occupying a range of sizes exceeding the field of view of a local observer, but often too small to be delineated on weather maps, are referred to as mesoscale systems or, simply, mesosystems. The size and lifetime of a mesosystem are positively correlated; large ones can maintain their identities for 24 hours or more.

The individual cells which make up mesosystems have typical lifetimes ranging from 15 minutes for small, convective cells to over 2 hours for snow-generating cells in stable air, [Langleben (11)]. The motion of mesosystems is accomplished through development and dissipation of cells, as well as by the movement of existing cells. Similarly, the movement of precipitation areas associated with cyclonic storms and fronts is accomplished, in part, by the formation and dissipation of mesosystems. To quote Austin and Blackmer (10) on cold-front precipitation in New England "The investigators were impressed by the fact that the precipitation pattern, relative to the moving surface front, is continually changing. For example, at one time there may be a frontal band and a prefrontal band and then an hour later the prefrontal band will have

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disintegrated into an isolated shower, or isolated showers will develop into a band, and so forth." From the synoptic point of view, then, the instantaneous distribution of precipitation is a random sample of a function whose average value, computed over several hours or several thousand square miles, is correlated with the existing pressure and temperature fields and, hence, with the major cloud systems. A recent paper by Nagle (12) comparing precipitation patterns, integrated over periods of up to six hours, with TIROS photographs illustrates this point quite clearly. Examination of cases in which close agreement exists between synoptic-scale weather maps and instantaneous precipitation patterns shows that each one usually involves a large, intense mesosystem, which effectively constitutes an entire storm at the time of observation, e.g. Ref. (6).

There is another possibility to be examined, namely, that precipitation echo types could be used to identify fronts and pressure patterns, even though their positions could only be estimated. Studies by Boucher (13), Ligda et al (14), and Kreitzberg (15) show that there is some correlation between echo type and synoptic situation, but no clear-cut distinctions. For example, in an open-wave cyclone, thunderstorms are most apt to occur along the cold front, but they can occur near the warm front and in the warm sector as well. Therefore, it would be impossible to base synoptic analyses of sparse-data regions upon precipitation data alone.

B. The Statistics of Precipitation

The difficulties in relating short-lived precipitation patterns to synoptic-scale weather systems have led many investigators to use statistical terms in describing precipitation. A useful concept in this approach is the precipitation eddy spectrum, the transform of the correlation coefficient, which can be computed in both the space and time domains. It is apparent that the common classification of precipitation echoes on radar screens as continuous, showery, or mixed is a description, in qualitative terms, of the eddy spectrum. Analysis of precipitation echoes has shown that the space-eddy spectrum is essentially continuous over a range of eddy diameters from 1 to 500 miles, with a concentration in the range from 50 to 100 miles [Noel and Fleisher (16)]. Similar results are found for the time-eddy spectrum, with the periods represented ranging from a minute or so up to several hours.

As one proposed weather radar satellite system (5) calls for observations in a 20-mile swath, study of the correlation of maritime precipitation echoes in 20-by-20 mile blocks has bben carried out to evaluate the usefulness of such observations. The datum studied was the number of 4-by-4 mile elements in each block containing precipitation echoes. Computations of correlation and autocorrelation coefficients were made for picket ship stations off Vancouver Island, Oregon, and California. The results of the spatial correlation study are shown in Fig. 2. No significant improvement in estimates of the number of elements containing echoes is possible for areas more than 50 miles from the region observed. The autocorrelation coefficients (not shown) indicate that useful extrapolation in time, i.e., persistence forecasting, is limited to about an hour.

A trial with 40-by-40 mile blocks yielded essentially the same results. This suggests that, in many cases, the long wavelength components of the eddy spectrum are of negligible importance, and that observations in a wide swath of, say, 100 miles cannot be extrapolated much further than those in a 20-mile swath.

The decrease in autocorrelation coefficients is due in part to translational effects. However, adoption of a frame of reference moving with the precipitation elements merely slows the decrease, rather than preventing it. Some improvement over mere persistence forecasting can be achieved with radar data from ground stations by extrapolating positions of cells and mesosystems using observed velocities [Wilson and Kessler (17)]. However, no determination of cell velocities can be made from a single satellite speeding past at several miles per second.

3. POSSIBLE APPLICATIONS OF PRECIPITATION DATA FROM SATELLITES

The potential value of precipitation data from satellites in local, mesoscale, and synoptic-scale applications will now be considered. The information could conceivably have operational or research value, or both, in any one of these size ranges.

Any device used to observe precipitation systems on a given scale should up-date its information several times during the lifetime of such systems. If it does not, it cannot provide a reliable input to operational than climatological data for the research worker.

A single satellite in a polar orbit, returning to a given part of the earth twice each day, is obviously unsuited to observation of local and mesoscale precipitation systems, regardless of the instantaneous coverage it provides. Complex orbits could be worked out to improve coverage in certain areas at certain times. The time interval between observations in a particular part of the world cannot be reduced to less than one orbital period, however, and this interval cannot be maintained in any given area for more than a few orbits at a time. Therefore, practical applications for precipitation data from satellites must be sought on the synoptic scale. This makes sense in another way. A satellite's most obvious advantage is its ability to probe remote areas, and it is a general rule in weather observing that interest in detail diminishes with distance. For example, an operational meteorologist is indifferent to mesoscale structure of a storm 1,000 miles away from the area for which he is to issue forecasts.

For observations on the synoptic scale, the motion of the satellite becomes a handicap, rather than an asset. If the radar proposed in Ref. 5 could view a 20-mile strip continuously, it could average over time to filter out local variations and assess the large-scale systems passing through. On an instantaneous basis, however, a 20-mile cut through a cluster of showers can yield results indistinguishable from those obtainable from a major frontal storm. If a satellite radar or other precipitation-monitoring device is to provide a significant input to synoptic meteorology, either for operational or research applications, its coverage must be on a broad scale, in swaths several hundred miles wide.

For operational purposes, the data would have to be up-dated once every hour or so [Jones et al (18)], a requirement that cannot be satisfied by a single satellite. If the data were to be used in climatological studies, less frequent up-dating would be acceptable. However, it should be noted that if a radar set were used as the sampling device the resulting data would be of limited value, even to climatologists. Radar reflectivity is not a unique function of rainfall rate; rainfall rate estimates based upon radar measurements have inherent uncertainties of up to 50% in addition to those which might arise from equipment malfunction. Such data would be virtually useless in studies of the atmospheric heat budget, which is one suggested application for global precipitation data.

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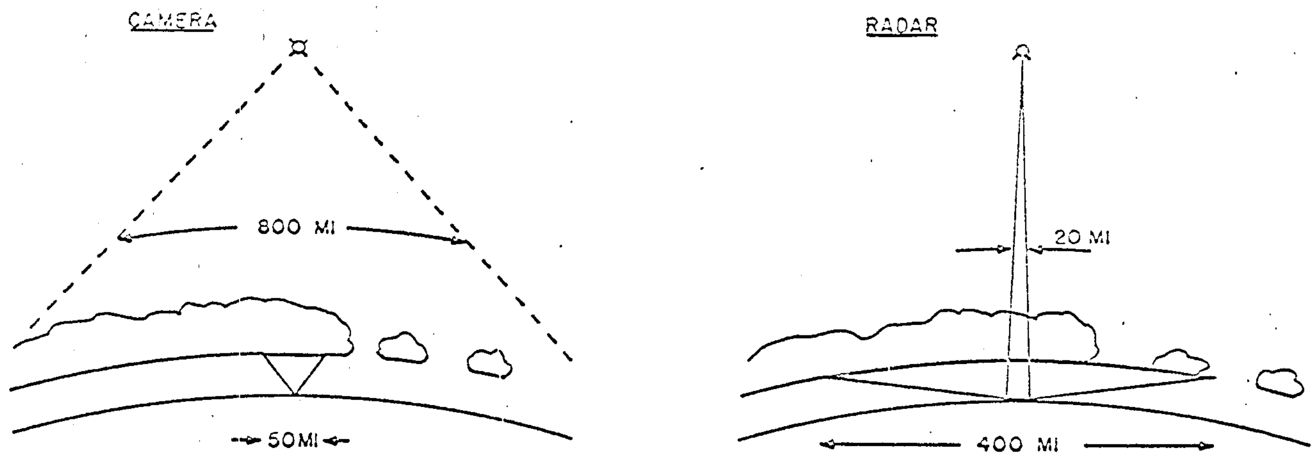

FIG. 1
FIELDS OF VIEW OF SATELLITE-BORNE vs. GROUND-BASED INSTRUMENTS

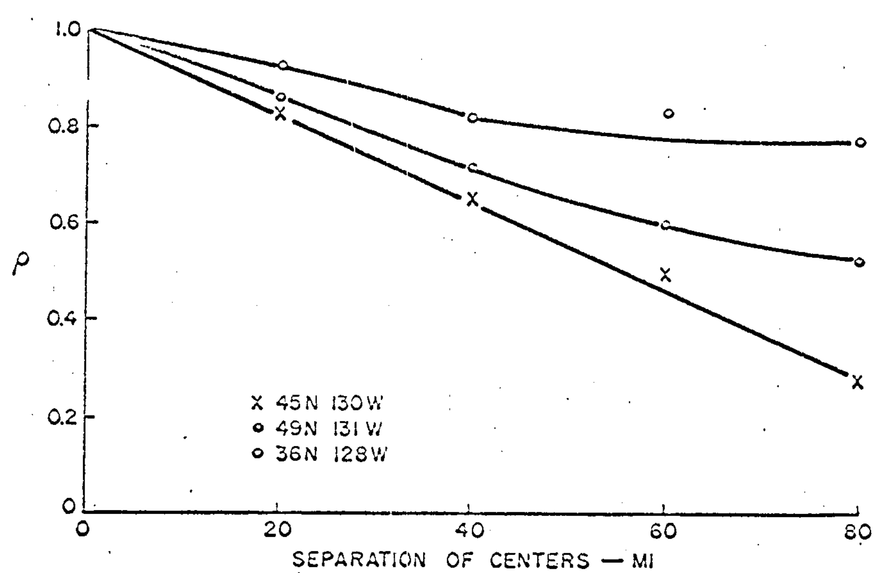

FIG. 2
CORRELATION COEFFICIENTS FOR PRECIPITATION IN 20-BY-20 MILE SQUARES